

HIGH-RESOLUTION OBSERVATIONS OF LOW-FREQUENCY JOVIAN RADIO EMISSIONS BY CASSINI

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Abstract

The Cassini spacecraft, en route to Saturn, executed its closest approach to Jupiter on December 30, 2000, at a distance of 137 Jovian radii. One of the capabilities of the radio and plasma wave science investigation is the ability to make high spectral and temporal resolution observations at frequencies from as low as a few Hz to 16 MHz using a combination of the investigation's high frequency receiver and wide-band receiver. These high-resolution capabilities were used to obtain brief snapshots of the spectral and temporal detail of narrow and broad-band kilometric radiation, Jovian type III bursts, and low-frequency narrow-band bursty emissions, many for the first time. The goal of this report is to show the variety of spectral and temporal fine structure of low-frequency Jovian radio emissions to further characterize each.

1 Introduction

The Cassini flyby of Jupiter in late 2000 and early 2001 provided an opportunity to significantly extend the characterization of Jovian radio emissions by using features of the Cassini radio and plasma wave science (RPWS) instrumentation that have not been available, previously, at Jupiter. In this paper, we utilize the Cassini wide-band receiver to examine the fine spectral and temporal detail of low frequency Jovian radio emissions, in many cases for the first time.

Ground-based observations are necessarily restricted to the frequency range generally above about 10 MHz because of the terrestrial ionospheric cutoff. Space-based observations are primarily from the Voyager planetary radio astronomy and plasma wave instruments, Ulysses, Galileo, and some distant observations by the WIND spacecraft. Voyager's

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temporal resolution was of order 5 seconds and spectral resolution was typically 20 kHz. It did carry a wide-band receiver with maximum frequency of about 12 kHz, however, which provided very high resolution observations of the lowest frequency emissions. Galileo's typical temporal resolution was of order 20 seconds, but had spectral resolution $\Delta f/f$ of approximately 10%. It, too, carried a wide-band receiver with both a 10-kHz and an 80-kHz bandwidth mode, but because of the very limited downlink capability on that spacecraft (due to a failure in the high gain antenna), very few wide-band data covering Jovian radio emissions were obtained. Ulysses observations were limited to frequencies below 940 kHz and had temporal resolution of about two minutes and spectral resolution of 20–30% above 52 kHz. (Higher temporal resolutions were obtained, but these have not been exploited, yet.) WIND makes all of its Jovian observations from Earth orbit, hence, does not have the signal-to-noise required to make high-resolution observations.

Cassini carries the most sophisticated radio astronomy investigation ever to have visited Jupiter. Overall, it covers the frequency range from 1 Hz to 16 MHz using a suite of receivers designed to obtain both moderate resolution survey observations and high-resolution measurements in tunable bandpasses across the entire 16 MHz range. A detailed description of this instrument is provided by Gurnett et al. [2001b]. Since this paper primarily utilizes the wide-band receiver, we'll only address its capabilities here. The Cassini RPWS wide-band receiver has two basic analysis ranges; 60 Hz to 10.5 kHz and 0.8 to 75 kHz. One antenna (typically the electric dipole, but also selectable are an electric monopole, a magnetic search coil, or a Langmuir probe) is used as input at any given time. The bandpass filter is followed by an automatic gain control amplifier and an 8-bit analog-to-digital converter. For the 10.5-kHz mode the sampling rate is 27.8 kHz, and for the 75-kHz mode the sampling rate is 222.2 kHz. A special mode of this receiver using the 75-kHz bandpass filter allows for the analysis of a 25 kHz-wide-band which is down-converted from the high-frequency receiver at frequencies tunable from 125 kHz to 16 MHz.

The Cassini Jupiter flyby trajectory was designed solely to optimize the flight time to Saturn, at which the spacecraft will go into orbit in July 2004. It is a relatively distant flyby with a closest approach distance of just under 137 Jovian radii (R_J). Figure 1 shows the trajectory of Cassini in Jupiter-centered coordinates for a period of about six months centered on closest approach, which occurred on December 30, 2000. Included for reference are the bow shock (BS) and magnetopause (MP) models based on the Voyager 1 flyby [Lepping et al., 1981a].

2 Broad-band kilometric radiation

Broad-band kilometric radiation (bKOM) usually occurs from as low as 10 kHz to as high as 1 MHz and is thought to be generated on auroral field lines on L-shells much larger than 12 via the cyclotron maser instability [Warwick et al., 1979a; Kaiser and Desch, 1980; Desch and Kaiser, 1980; Leblanc, 1988; Lecacheux et al., 1992; Ladreiter et al., 1994b; Zarka, 1998; Zarka et al., 2001a]. Voyager studies [Kurth et al., 1980b] showed that this emission is typically observed above about 10 degrees magnetic latitude because of shadowing near the magnetic equator by the dense Io plasma torus. Voyager also

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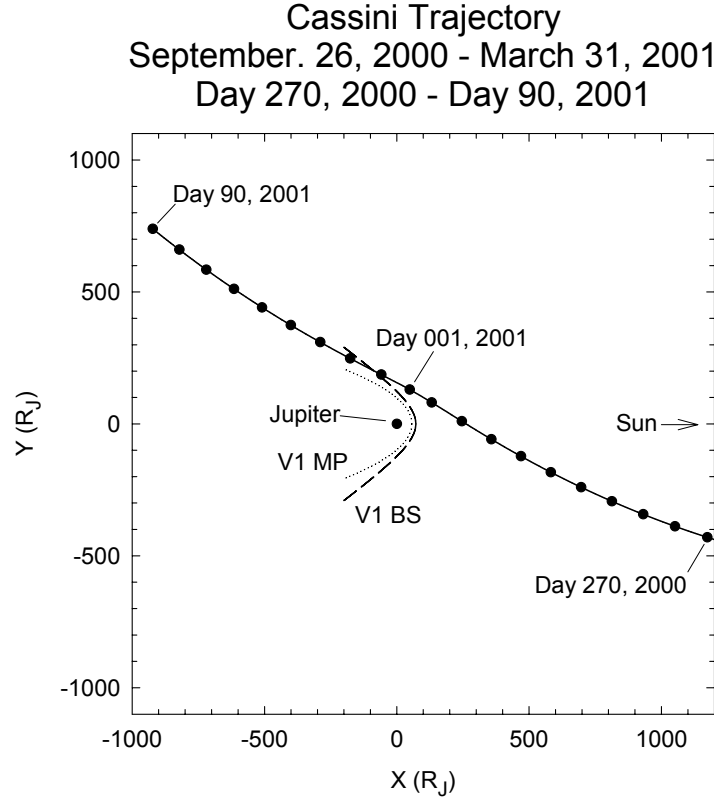


Figure 1: The Cassini trajectory relative to Jupiter for the 6 months centered on closest approach.

showed the first temporal structure of these emissions [Warwick et al., 1979a], showing that they exhibit considerable intensity variations that drift upwards or downwards in frequency on time scales of minutes. The emissions generally last longer (are seen for a larger portion of a Jovian rotation) at lower frequencies. Galileo further showed that broad-band kilometric radiation often appeared as a series of rapidly drifting tones, mostly increasing in frequency with time [Kurth et al., 1997c]. Kurth et al. [1979a] showed fine structure in the Voyager 12-kHz wide-band data in one instance with very narrow-band, rapidly downward-drifting tones, but this is at such low frequencies, it is not certain how indicative this structure is to the bulk of the emission. The single high-resolution 80-kHz wide-band observation scheduled for Galileo before it moved to an equatorial orbit (hence, residing almost entirely in the equatorial shadow zone) fell during a rare occasion when the bKOM emission disappeared for more than a day.

The Cassini observations of interest to the study of bKOM fine structure are short observations using the 75-kHz wide-band receiver that often can observe the low-frequency portion of the emission. Opportunities for these observations typically occurred one or two times per week in sets of 1 to several ~ 6 -minute observations each hour. Since these

did not always occur when the magnetic latitude of Cassini was greater than 10° , many of the observations did not provide information on the broad-band kilometric radiation fine structure. However, sufficient examples were obtained to show a wealth of variability in the frequency-time appearance of these emissions. Figures 2–5 show four such examples.

In the first example (Figure 2) of broad-band kilometric radiation, acquired on October 31, 2000, we show the survey observations with moderate spectral and temporal resolution in the top panel for context and the wide-band frequency-time spectrogram in the lower panel. In each, the intensity of waves as a function of frequency (ordinate) and time (abscissa) is displayed using a color scheme indicated by the color bars. The lower resolution display utilizes a logarithmic frequency axis and the wide-band data are displayed with a linear frequency scale, since the Fourier components are linearly spaced. In the bottom panel of Figure 2, a large number of very narrow-band drifting tones can be seen in the bKOM spectrum superimposed on a more continuous background emission. The drifting tones have bandwidths of order 500 Hz or 1%, but the tones appear to be unresolved and may actually be even narrower. The drift rate is -1 to -2 kHz/s near 60 kHz, but the rate appears to slow to -0.5 to -1 kHz/s at lower frequencies (30 to 40 kHz). Interestingly, the fine structure reported by Kurth et al. [1979a] looks very similar to these. Similar narrow-band drifting structures have been observed in auroral kilometric radiation (AKR) at Earth by Menietti et al. [1997, 2000]. On the other hand, the structures in Figure 2 are not similar to the Jovian bKOM structures shown in Kurth et al. [1997c]; the latter have a completely different time and spectral scale. Also, while there are some similarities in drift rates and bandwidth to the fine structure observed in the terrestrial ISEE data [Gurnett et al., 1979], the structures in Figure 2 are much more uniform than the somewhat chaotic AKR examples which exhibit both up- and down-going emissions that often erratically change their drift rate and direction. Zarka [1998] provides an overview of planetary radio emission fine structure as well as a compendium of theories offered to explain them. Narrow-band structures in AKR have been modeled, for example, by Pritchett et al. [1999], but the explanation of frequency drifting is a subject of ongoing work. Ellis [1974] and most recently Carr and Reyes [1999] discuss the adiabatic bounce motion of energetic electrons as a mechanism for the drift of Jovian S bursts. While S bursts are in the decametric regime, it is likely that the generation of bKOM and the decametric emissions have a common basis in the cyclotron maser mechanism and that mechanisms for drift in one frequency range may also be appropriate for the other. The basic idea is that the motion of electrons upward along a magnetic field line results in their motion on a path with a continuously decreasing magnetic field strength, hence, electron cyclotron frequency. Zarka et al. [1996] showed that such a model could fit the average observed drifts of S bursts using ~ 5 keV electrons in their adiabatic bounce motion.

The example of broad-band kilometric radiation in Figure 3 appears to lack any but the largest spectral and temporal structure, merely showing the morphology of the large drifting structures seen in the lower resolution (upper) panel. The example in Figure 4 again shows fine structure, but significantly different from that in Figure 2. Here the drifting features are much broader, a few kilohertz or nearly 10%. And, the structures are nearly constant in frequency, or slowly rising. What fine structure exists in this example is considerably less organized than the drifting structures in Figure 2.

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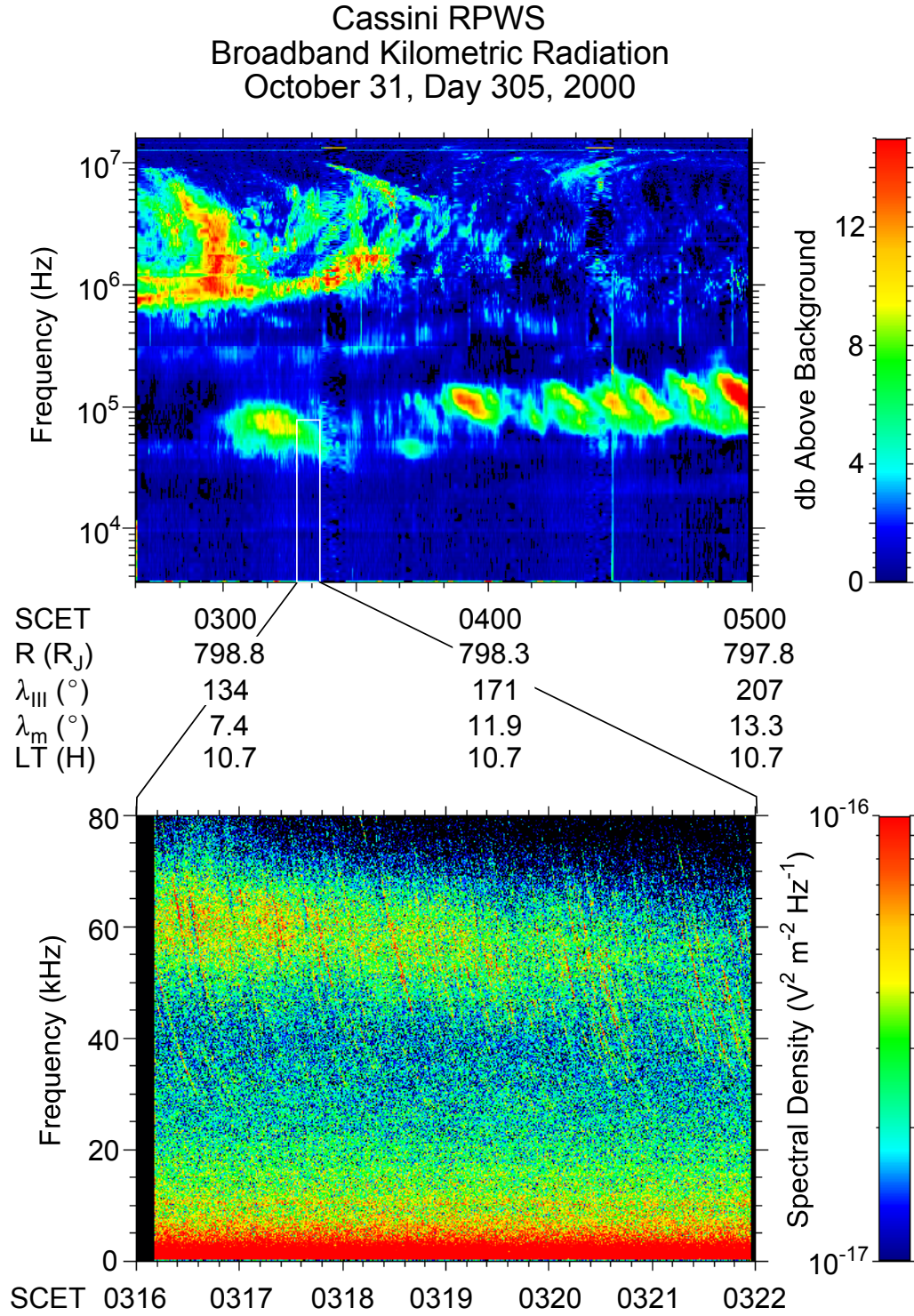


Figure 2: An example of downward drifting fine structure in *bKOM*.

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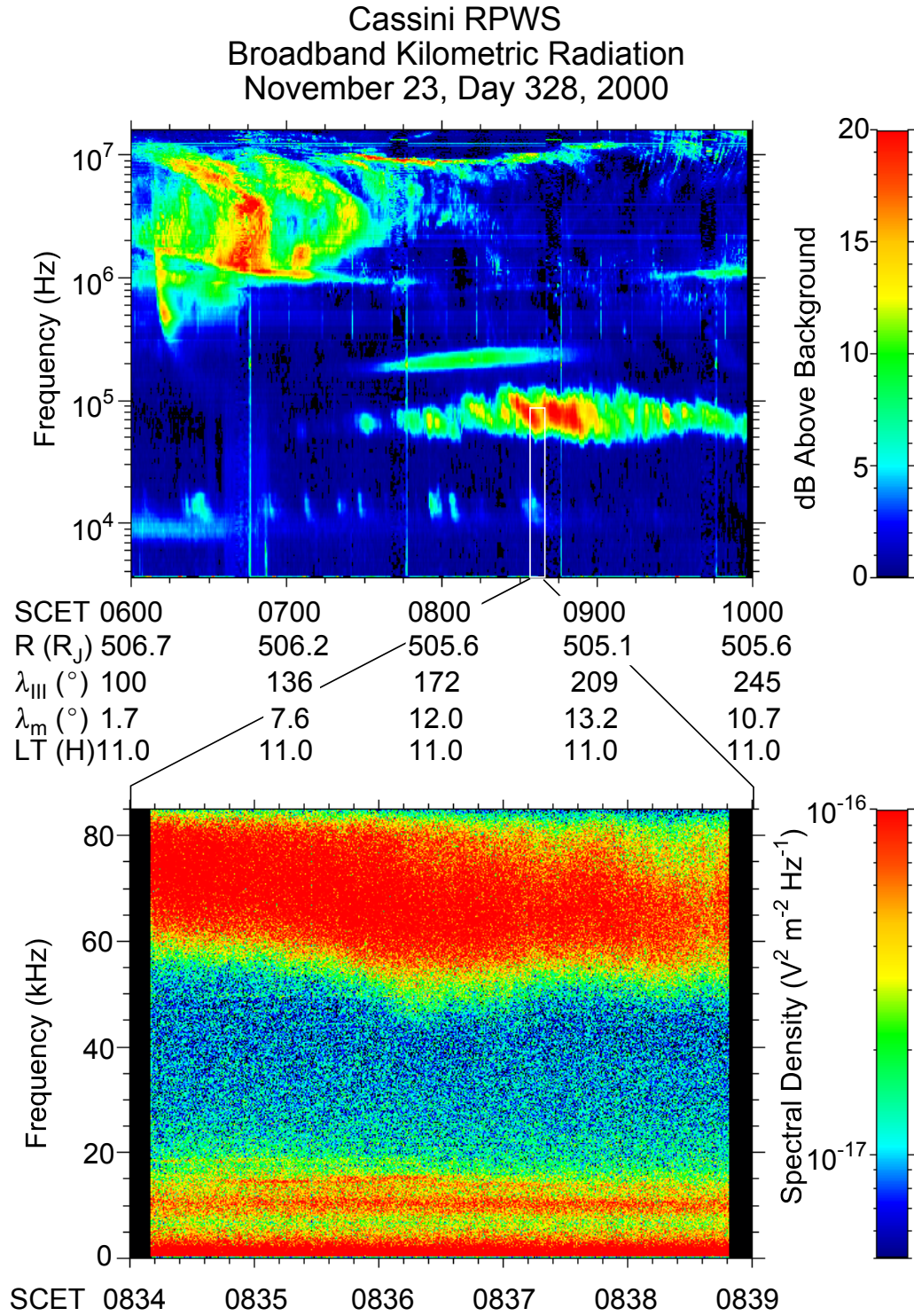


Figure 3: An example of *bKOM* with little or no fine structure.

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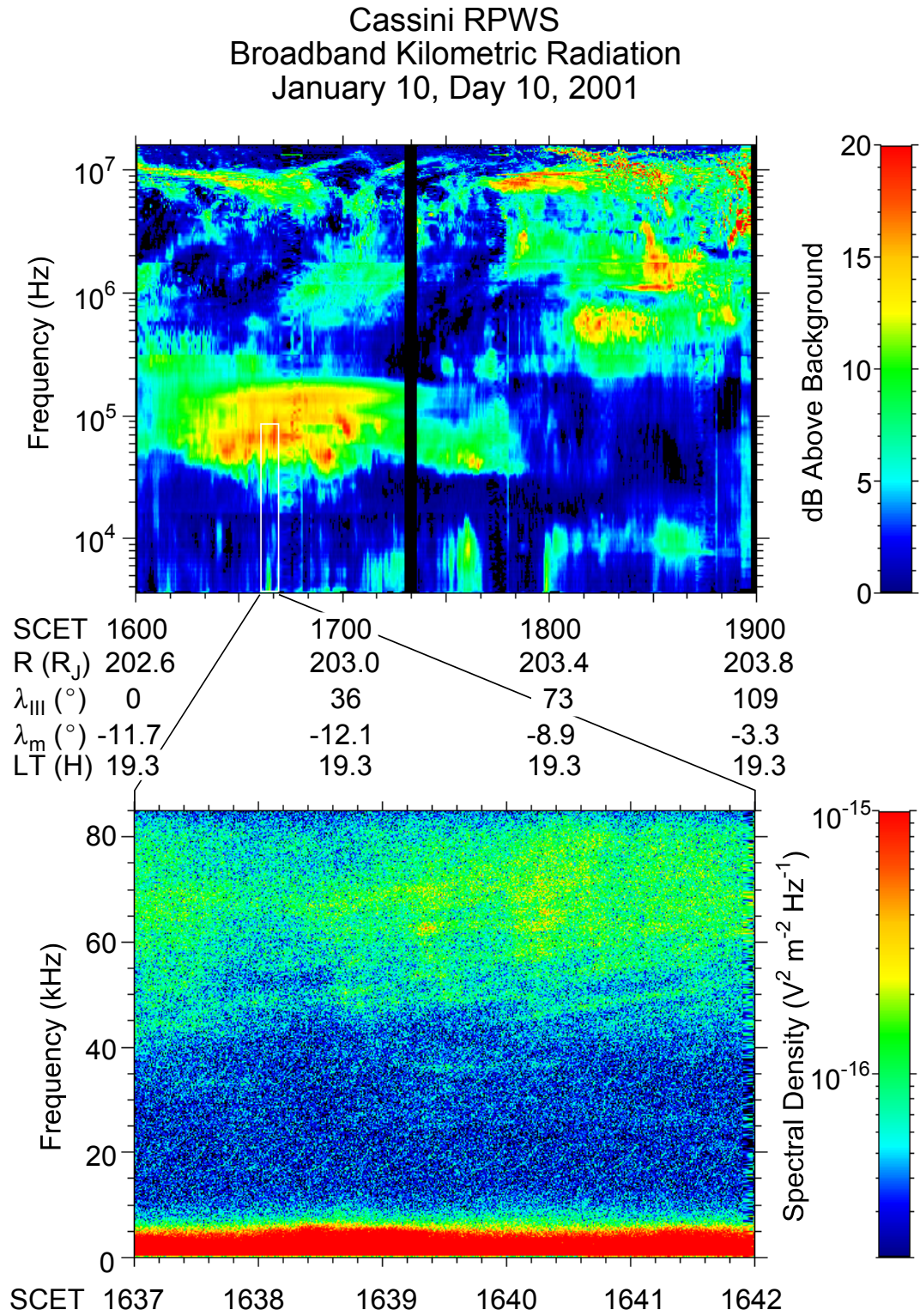


Figure 4: In this example, the fine structure in bKOM is poorly organized and shows a variety of scales.

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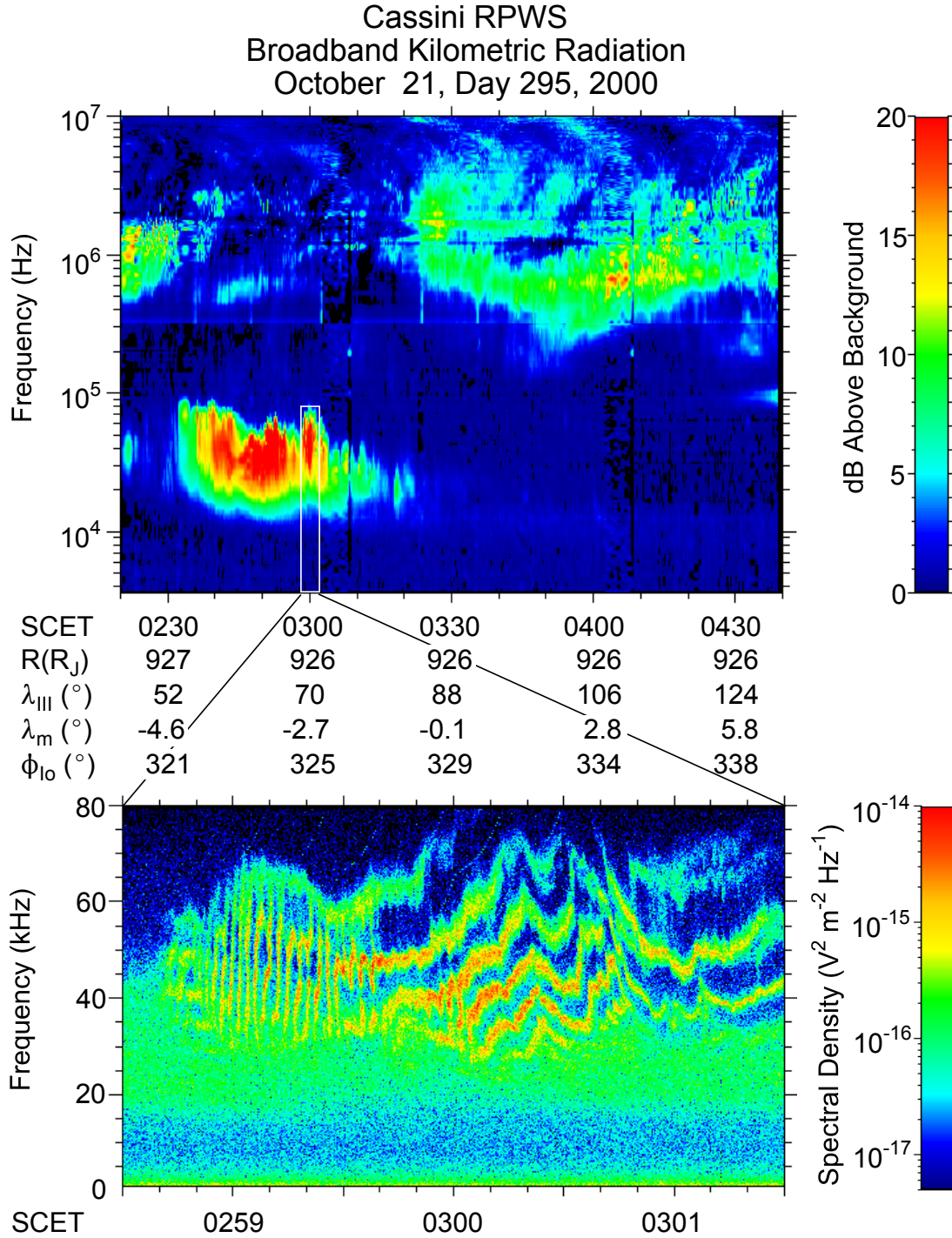


Figure 5: An extraordinary example of complex structure in bKOM. The banded structure suggests a source like escaping continuum radiation, but early in the interval the structure is suggestive of propagation effects.

Perhaps the most extraordinary example of fine structure in broad-band kilometric radiation is shown in Figure 5. There is clear evidence of nearly harmonically related bands in the latter half of this event. The harmonically spaced banding might be expected from radiation from electrostatic upper hybrid waves on a density gradient via some mode-conversion process such as those suggested for non-thermal continuum radiation at Earth and Jupiter [see, for example, Jones, 1980; and Rönnmark, 1983]. Upper hybrid emissions are a common feature of the Io plasma torus inside of about 12 R_J [Kurth et al., 1980a; Birmingham et al., 1981; Meyer-Vernet et al., 1993]. Since intense electrostatic upper hybrid bands of the type which could be the source of reasonably intense electromagnetic bands are special cases of electron cyclotron harmonic emissions, the band spacing would be the electron cyclotron frequency at the location of the density gradient [Kurth et al., 1979b]. At about 0300:15 spacecraft event time (SCET) the band spacing, going from the lowest band to the highest is approximately 8, 11, 11, and 15 kHz. Since the density gradient could extend over an appreciable radial distance, the magnetic field strength would also vary, hence, the bands would not necessarily be strictly harmonically related. In such a scenario, the spacing would increase from the lowest to highest frequency bands. The electron cyclotron frequency is of order 12 kHz and the electron plasma frequency is several tens of kHz to ~ 100 kHz at a radial distance of about 10 R_J [Kurth et al., 2001c], hence, this would be a suspected radial distance for the source region. However, this explanation would be inconsistent with the identification of these emissions as broad-band kilometric radiation since bKOM is generally believed to be the result of the cyclotron maser instability and is usually emitted in the extraordinary mode vs. ordinary mode for continuum radiation. Furthermore, the rapid oscillation in frequency of the bands would seem to require substantial motions of the magnetic field relative to the density gradient to have the upper hybrid resonance frequency drift so dramatically on such short time scales.

The situation for the earlier portion of the event is dramatically different and even more difficult to understand. Here, the drifting is so severe that it masks any harmonic relationships which may be present. Many of the emission features are almost vertical in frequency-time space and several show inflection points, reversals in the sign of frequency drift one, two, and possibly even more times. The nearly vertical elements merge into the more easily seen banded structure near 0259:30 SCET. In some respects, the earlier frequency-time structure is suggestive of fringes, hence, a propagation effect comes to mind. However, the evolution of the “fringes” into the banded structure would argue for simply more violent fluctuations in the source region at the earlier times.

The structures shown here have been seen (not nearly so clearly) in only a few other examples obtained by Cassini to date. Most of them are at small southern magnetic latitudes as is the case for the example in Figure 5. There are two northern hemisphere cases and one is above 13 degrees magnetic latitude. Given the broad-band kilometric radiation shadow zone found by Voyager extending $\sim \pm 10$ degrees from the magnetic equator, it is somewhat anomalous to find bKOM here. If the shadow zone is truly due to propagation effects, then it is also possible that some of the frequency-time structure seen in Figure 5 is due to propagation effects through the Io plasma torus. In short, we have no reasonable model for explaining the bizarre frequency-time structure in this example.

3 Narrow-band kilometric radiation

Narrow-band kilometric radiation (nKOM) was first identified by Warwick et al. [1979b] and studied in detail by Kaiser and Desch [1980]. These emissions are centered between 60 and 150 kHz, similar to the central frequency for broad-band kilometric radiation, but have much smaller overall bandwidth of the order of 40 to 80 kHz and a much smoother temporal variation. The source of these emissions was deduced from Voyager observations to be near the magnetic equator at the outer edge of the Io torus (radial distances of $\sim 10 R_J$) [Kaiser and Desch, 1980]. More definitive direction-finding measurements by Ulysses [Reiner et al., 1993a] show numerous sources in this radial distance range moving about Jupiter at nearly the corotation rate. Drifting of the emissions at a few percent below corotation was reported by Kaiser and Desch [1980] and Kurth et al. [1980b]. The consensus had been that these emissions are generated via mode conversion from electrostatic upper hybrid emissions in the outer reaches of the Io torus [see Kaiser, 1989 and references therein] although the Reiner et al. determination of the emissions propagating in the extraordinary mode would seem to contradict this.

Figure 6 shows an example of a 25-kHz band centered at 125 kHz in an nKOM event using the high-frequency down-conversion mode of the wide-band receiver coupled with the Cassini high frequency receiver. The narrow-band tone at 125 kHz is interference. While there is some variation in intensity over the duration of this data set and some evidence for this variation to be a function of frequency, there is no evidence of any fine structure on frequency scales of 10 kHz or less or time scales of a minute or less. Because of the relatively smooth temporal and spectral nature of these emissions derived from the earlier studies, it is not surprising to find a lack of structure in the high-resolution Cassini observations. On the other hand, if these emissions are the result of mode-conversion from electrostatic upper hybrid bands, one might expect to see numerous narrow-band structures comprising the overall nKOM spectrum.

4 Quasi-periodic radio bursts

Figure 7 shows an example of Jovian type III bursts [Kurth et al., 1989] observed by Cassini on October 4, 2000, approximately 0.5 AU from Jupiter. These are more recently referred to as quasi-periodic (QP) bursts by MacDowall et al. [1993] because they were seen with periodicities of about 15 or 40 minutes by Ulysses during its 1992 Jupiter flyby. The example in Figure 7 shows the apparent dispersion in these events reported by Kurth et al., which has been tentatively explained by Desch [1994] as a propagation effect in the Jovian magnetosheath and also the 1–2 minute sub-periodicity originally reported by Kurth et al. Kaiser et al. [2001, this issue] provide a more complete background and a summary of the Cassini observations at lower resolution, detailing a rather complex picture, especially on the apparent lack of systematic occurrence of either 15- or 40-minute periodicities with respect to any obvious geometric parameter such as local time.

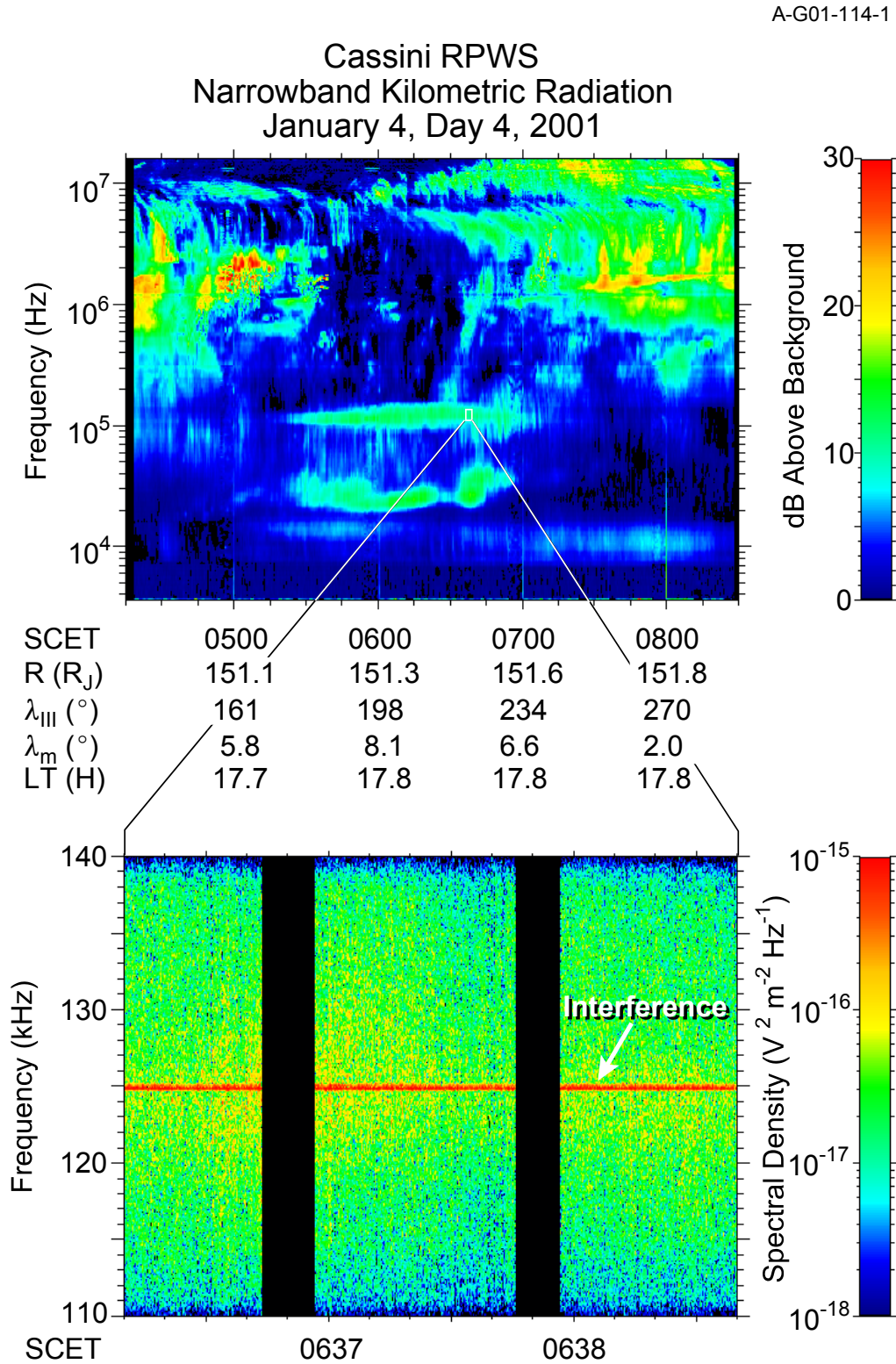


Figure 6: This example of nKOM shows, as expected, little evidence of fine structure in either time or frequency.

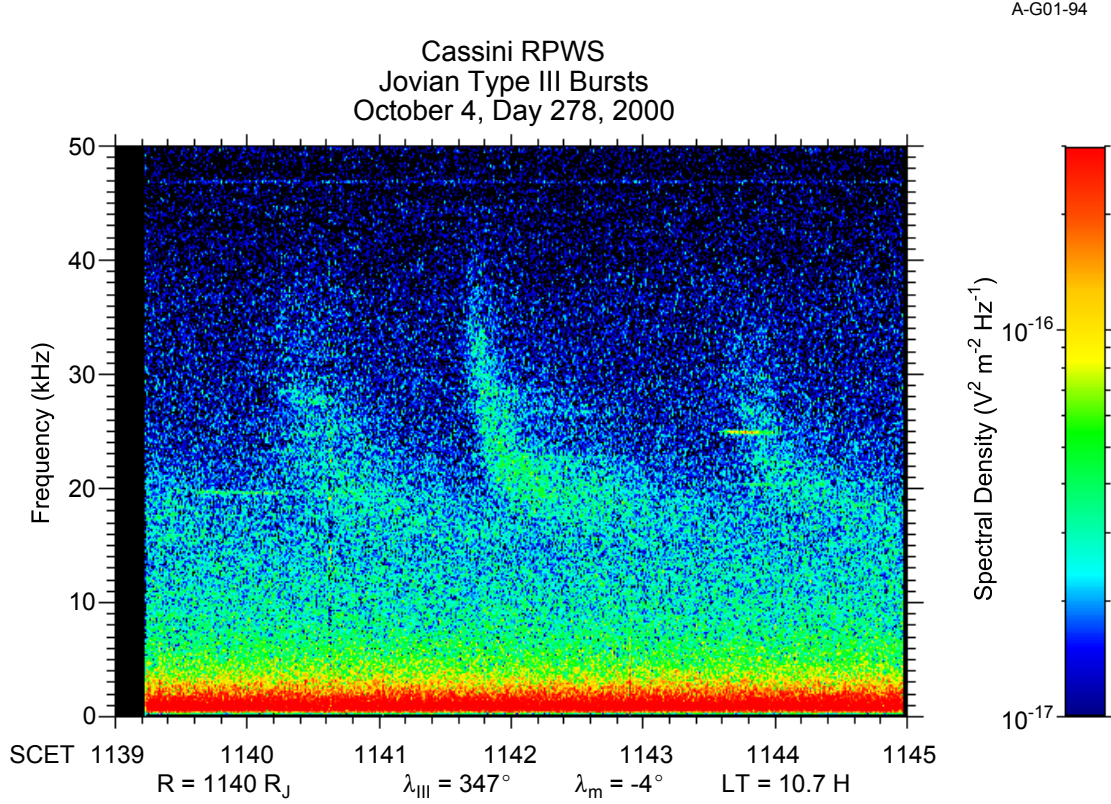


Figure 7: Examples of Jovian type III (or quasi-periodic) radio bursts with their characteristic dispersive-like frequency-time structure.

5 Low-frequency narrow-band bursty emissions

One possibly unreported phenomenon observed by Cassini in the Jovian low-frequency radio spectrum are narrow-band bursty emissions such as those shown in Figure 8. These are most often observed from a few tens of kHz down to the magnetosheath plasma frequency that is typically 10 kHz or less. They have bandwidths of the order of a few percent of the center frequency and often show amplitude variations on time scales of less than a minute, although many times the emissions apparently extend for much longer periods. Note that there are two examples of these emissions in Figure 7 at about 23 kHz centered at 1144 SCET and also a somewhat weaker band at 20 kHz centered near 1140 SCET. Narrow-band electromagnetic emissions were reported by Gurnett et al. [1983] and also Kurth [1992] based on Voyager wide-band observations below about 12 kHz. It is likely that the more continuous bands observed by Cassini are similar to those reported earlier. However, there was no evidence for the rapid temporal variations, or burstiness seen here. Of interest are similar narrow-band bursty emissions observed by Voyager at Uranus [Kurth et al., 1986]. In this paper Kurth et al. suggested that the narrow-band

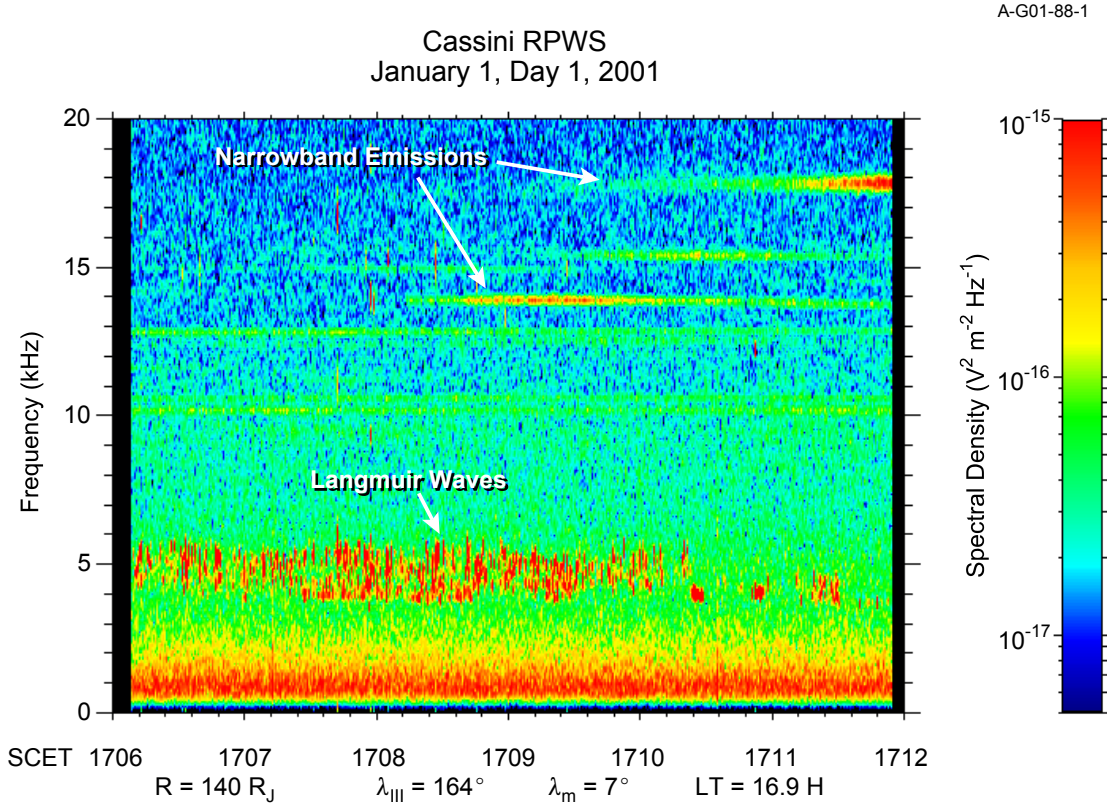


Figure 8: Narrow-band bursty emissions at frequencies above the Solar wind plasma frequency. These are likely similar to narrow-band electromagnetic bands discovered by Voyager, but display considerably more temporal variation than the Voyager examples.

emissions were likely generated by the same mechanism as escaping continuum radiation, i.e., via mode conversion from electrostatic upper hybrid bands in the magnetosphere and that the burstiness could be an effect of a strongly beamed source which is rotating with the planet's magnetic field.

6 Summary

This paper presents high temporal and spectral resolution observations of several of the low-frequency Jovian radio emissions using new capabilities afforded by the Cassini radio and plasma wave receiver. The basic findings include:

1. Broad-band kilometric radiation displays a variety of fine structure, from none at all to well-organized downward drifting narrow-band emissions and sometimes wildly chaotic banded structures.

2. As expected from earlier studies, we found no evidence of fine structure in the narrow-band kilometric radiation.
3. Cassini observes the type III burst-like appearance of Jovian type III or quasi-periodic bursts similar to that reported on the basis of Voyager observations.
4. While Voyager had revealed the existence of low-frequency narrow-band electromagnetic emissions, the Cassini observations show that, at times, these can be bursty and display rapid variations in intensity on time scales of less than a minute.

Perhaps the most interesting of these results is the wide range of variability in the broad-band kilometric radiation fine structure. It is possible to speculate that this variety is due to either variability in the source region with some characteristics similar to AKR fine structure or decametric S bursts or to propagation effects due, presumably, to the passage of the waves through some portion of the Io torus. Of course, some combination of source and propagation effects is likely to form the basis for the complete explanation of these observations. Given the low magnetic latitude of many of the bKOM observations and the large variety of structure apparent, it is at least possible that there are subclasses of this radio emission type which heretofore have gone un-noticed.

Acknowledgements: The authors are grateful to T. F. Averkamp, W. T. Robison, R. A. Johnson, L. J. Granroth, J. B. Groene, and A. M. Persoon for their masterful and efficient development and operation of the Cassini RPWS data processing and analysis system.

This research was supported by NASA with contracts 958779 and 961152 with the Jet Propulsion Laboratory.

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